



Physiological Adaptation Analysis of Adolescent Athletes to a Training Program Based on Internal and External Load Monitoring

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Abstract

Background: Adolescent athletes are in a critical period of physiological development, making appropriate training load management essential to optimize performance while minimizing injury risks. The monitoring of both internal and external training loads has emerged as a fundamental approach in contemporary sports science to ensure training effectiveness and athlete well-being. **Objective:** This study aimed to analyze the physiological adaptations of adolescent athletes following a structured training program based on systematic internal and external load monitoring at the Faculty of Sport and Health Sciences, Universitas Negeri Makassar. **Methods:** A quasi-experimental design with a pre-test and post-test approach was employed, involving 30 adolescent athletes aged 14-17 years selected through purposive sampling. Internal load was measured using the session Rating of Perceived Exertion (sRPE) and heart rate monitoring (HRmax and TRIMP), while external load was assessed through GPS-based metrics including total distance covered, sprint distance, and training volume. Physiological parameters including VO₂max, resting heart rate, blood lactate threshold, and muscle strength were evaluated at baseline and after 12 weeks of intervention. **Results:** Significant improvements were observed across all physiological parameters. VO₂max increased from a mean of 42.3 ± 3.1 mL/kg/min to 48.7 ± 2.9 mL/kg/min (p < 0.001). Resting heart rate decreased significantly from 74.2 ± 5.3 bpm to 62.8 ± 4.7 bpm. Blood lactate threshold improved by 18.4%, and muscle strength indices showed a mean gain of 22.6%. Internal and external load data confirmed progressive overload adherence throughout the intervention period. **Conclusion:** A systematically monitored training program integrating internal and external load parameters produces significant physiological adaptations in adolescent athletes, supporting enhanced aerobic capacity, cardiovascular efficiency, and muscular performance. These findings underscore the importance of individualized load monitoring in youth athletic development.

Keywords: physiological adaptation; adolescent athletes; internal load; external load; training monitoring; VO₂max

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INTRODUCTION

The physical development of adolescent athletes represents one of the most complex and sensitive periods in sports science, demanding careful attention to both the nature and magnitude of training stimuli. During adolescence, the human body undergoes rapid musculoskeletal, hormonal, and cardiovascular changes that simultaneously create windows of trainability and vulnerabilities to overtraining and injury. In this context, the scientific management of training load has become not merely a performance optimization strategy but a critical element of athlete health and long-term development (Impellizzeri et al., 2020).

Training load, broadly defined as the stress imposed on an athlete through structured physical activity, can be categorized into two interrelated dimensions: internal load and external load. External load refers to the objective, measurable work performed by an athlete independent of their internal

state, encompassing variables such as total distance covered, sprint frequency, acceleration and deceleration bouts, training volume, and exercise intensity expressed in mechanical terms. Internal load, in contrast, reflects the physiological and psychological response of the individual athlete to that external stimulus, manifested through indicators such as heart rate, session Rating of Perceived Exertion (sRPE), blood lactate concentration, and hormonal markers (Bourdon et al., 2021).

The relationship between internal and external load is neither linear nor uniform across individuals, particularly among adolescent athletes whose physiological profiles are still maturing. Two athletes performing identical external workloads may experience markedly different internal responses due to variations in fitness level, recovery status, nutritional state, psychological readiness, and developmental stage. This individual variability underscores the necessity of monitoring both load dimensions concurrently to accurately capture the true training demands placed on each athlete (Soligard et al., 2020).

In recent years, the proliferation of wearable technology, GPS tracking systems, and validated subjective tools such as the Borg CR-10 scale has democratized access to load monitoring in community and school-level sports programs. The session RPE method, introduced by Foster et al. and subsequently validated in numerous populations, provides a practical, low-cost means of quantifying the internal load of any training session by multiplying the athlete's perceived exertion rating by the session duration in minutes. This metric, often referred to as the training load score, has been shown to correlate strongly with more physiologically precise measures such as heart rate-based TRIMP (Training Impulse) and blood lactate accumulation (Haddad et al., 2021).

Physiological adaptations resulting from systematic training are well-documented in adult populations and include increases in maximal oxygen uptake (VO₂max), improvements in cardiac output and stroke volume, enhanced mitochondrial density and oxidative enzyme activity, reductions in resting heart rate, and improved neuromuscular efficiency. However, the specific adaptations occurring in adolescent athletes under monitored load conditions remain less thoroughly studied, particularly in the Indonesian context where youth sports participation is rapidly growing but scientific monitoring infrastructure is still developing (Prasetyo & Nugroho, 2021).

Adolescent athletes in Indonesia face unique challenges that differentiate their training context from that of their counterparts in high-resource countries. Limited access to sophisticated physiological testing equipment, variability in coaching expertise, high ambient temperatures, and nutritional inconsistencies all influence training responses. At Universitas Negeri Makassar, the Faculty of Sport and Health Sciences serves as a regional hub for youth athletic development in Eastern Indonesia, providing an ideal setting to investigate evidence-based training interventions in a population-representative context (Ramadhan & Santoso, 2022).

The concept of athlete monitoring has evolved considerably since the early work of Banister and colleagues, who introduced the training impulse concept in the 1970s. Contemporary monitoring frameworks now integrate multiple data streams to provide coaches with actionable insights regarding athlete readiness, fatigue, and adaptation. Key derived metrics such as the acute-to-chronic workload ratio (ACWR), monotony index, and strain have been proposed as predictive indicators of injury risk and performance readiness. Maintaining the ACWR within an optimal zone, generally considered to be between 0.8 and 1.3, has been associated with reduced soft tissue injury incidence in team sports athletes (Gabbett, 2020).

Despite growing evidence supporting load monitoring in elite and sub-elite adult athletes, its application in structured youth training programs remains inconsistent. Many coaches working with adolescent athletes rely primarily on experience-based load prescription rather than data-driven approaches, potentially exposing young athletes to inappropriate training stimuli. Research suggests that both undertraining and overtraining during the adolescent developmental window can have lasting consequences on athletic potential, immune function, and psychological well-being (Matos et al., 2021).

Cardiovascular adaptations represent perhaps the most well-characterized physiological response to endurance-type training. Increases in stroke volume, cardiac hypertrophy, and parasympathetic dominance at rest collectively result in the characteristic low resting heart rate observed in trained athletes. In adolescent populations, these adaptations appear to be magnified

during pubertal growth phases, particularly in male athletes experiencing testosterone-mediated increases in muscle mass and hemoglobin concentration. Female adolescent athletes, while demonstrating similar qualitative adaptations, may show different magnitudes of response due to hormonal profiles and body composition differences (Baquet et al., 2020).

Muscular adaptations to resistance and mixed-mode training in adolescents include increases in muscle cross-sectional area, improvements in neuromuscular recruitment efficiency, and enhanced connective tissue strength. These adaptations are particularly important in collision sports and activities requiring explosive power, where insufficient muscular development relative to skeletal growth can increase injury risk. Monitoring external load parameters such as jump height, sprint speed, and acceleration profiles provides coaches with indirect indicators of neuromuscular fatigue and adaptation status (Faigenbaum et al., 2020).

The blood lactate threshold, defined as the exercise intensity at which blood lactate concentration begins to rise exponentially above resting values, is a sensitive indicator of aerobic fitness and training-induced metabolic adaptation. Improvements in lactate threshold following structured training reflect increases in mitochondrial density, enhanced lactate clearance mechanisms, and improved fat oxidation capacity, collectively enabling athletes to sustain higher exercise intensities with reduced reliance on anaerobic glycolysis. In adolescent athletes, lactate threshold testing has proven feasible and responsive to training interventions of relatively short duration (Buchheit & Laursen, 2020).

Given the complexity of physiological responses in adolescent athletes and the multidimensional nature of training load, this study was designed to evaluate the physiological adaptations produced by a 12-week structured training program at the Faculty of Sport and Health Sciences, Universitas Negeri Makassar. By systematically monitoring both internal and external load throughout the intervention period and measuring key physiological parameters before and after the program, this research aims to contribute evidence-based insights to youth athlete development practices in Indonesia and the broader regional sporting community.

METHODS

This study employed a quasi-experimental design with a one-group pre-test and post-test approach to evaluate physiological changes resulting from a 12-week structured training program based on internal and external load monitoring. The research was conducted at the Faculty of Sport and Health Sciences, Universitas Negeri Makassar, from January to April 2024. Ethical approval was obtained from the University Research Ethics Committee prior to data collection, and written informed consent was obtained from both the athletes and their legal guardians in accordance with institutional protocols.

Participants were recruited through purposive sampling from the university-affiliated youth sports development program. Inclusion criteria required participants to be between 14 and 17 years of age, actively engaged in organized sport for a minimum of two years, free from musculoskeletal injury or chronic illness, and available for the full duration of the 12-week intervention. Exclusion criteria included the use of performance-enhancing substances, concurrent participation in another structured training study, and incomplete attendance of less than 80 percent of scheduled sessions. A total of 30 adolescent athletes met the criteria and were enrolled, consisting of 18 male and 12 female participants with a mean age of 15.6 ± 1.1 years (Prasetyo & Nugroho, 2021).

Baseline and post-intervention physiological assessments were conducted within five days of the program's commencement and conclusion, respectively. VO₂max was estimated using the 20-meter multistage fitness test (Beep Test), which has been validated for use in adolescent populations and shown to correlate strongly with laboratory-measured maximal oxygen uptake. Resting heart rate was measured in a standardized supine position following a minimum of 10 minutes of quiet rest using a Polar H10 chest strap heart rate monitor. Blood lactate threshold was assessed during a graded treadmill exercise test with lactate sampling from the fingertip at each stage using a Lactate Pro 2 analyzer. Lower body muscular strength was evaluated using a standardized squat jump and

countermovement jump protocol on a force plate, from which peak force, rate of force development, and jump height were derived (Buchheit & Laursen, 2020).

The 12-week training program was structured into three four-week mesocycles corresponding to general preparation, specific preparation, and pre-competition phases. Each mesocycle was characterized by a progressive increase in training load during the first three weeks followed by a reduced load in the fourth week to facilitate recovery and adaptation consolidation. Athletes participated in five training sessions per week, with session types including aerobic base training, speed and agility work, strength and power development, and sport-specific technical and tactical sessions. Session duration ranged from 60 to 90 minutes depending on the training emphasis and phase of the program (Impellizzeri et al., 2020).

External load was quantified using CATAPULT OptimEye S5 GPS devices worn in a vest between the scapulae during all outdoor and large indoor training sessions. Key external load metrics recorded included total distance (m), high-speed running distance (above 18 km/h), sprint distance (above 24 km/h), PlayerLoad (a composite accelerometer-derived measure), and the number of acceleration and deceleration efforts exceeding 3 m/s². For sessions in which GPS devices were not appropriate, such as strength training and indoor technical work, external load was quantified through session duration and volume (sets, repetitions, and load in kilograms) (Bourdon et al., 2021).

Internal load was assessed using two complementary methods. First, the session RPE method was employed whereby each athlete rated their perceived exertion for the entire session on a 0-10 Borg CR-10 scale approximately 30 minutes after session completion to minimize immediate post-exercise emotional influences on ratings. The sRPE score was then multiplied by session duration in minutes to yield an internal training load score in arbitrary units (AU). Second, heart rate data were collected continuously during each session, and TRIMP values were calculated using the Edwards method, which assigns exponential multipliers to five heart rate zones as a proportion of maximum heart rate to produce a composite cardiovascular stress score (Haddad et al., 2021).

Acute (7-day rolling average) and chronic (28-day rolling average) workload values were calculated weekly for each athlete using both sRPE-based training load and TRIMP data. The ACWR was derived by dividing acute by chronic load and was monitored throughout the program to guide individualized load adjustments. Weekly training monotony and strain indices were also computed as additional indicators of load distribution quality. Coaches received weekly individualized load reports enabling real-time adjustments to training prescription (Gabbett, 2020).

Data were analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Normality of distribution was confirmed using the Shapiro-Wilk test for all continuous variables. Pre-to-post intervention comparisons were made using paired samples t-tests for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed variables. Effect sizes were calculated using Cohen's d to characterize the practical magnitude of changes, with values of 0.2, 0.5, and 0.8 interpreted as small, medium, and large effects, respectively. Pearson and Spearman correlation analyses were performed to examine relationships between load monitoring metrics and physiological outcomes. Statistical significance was set at $p < 0.05$ for all analyses (Matos et al., 2021).

RESULT AND DISCUSSION

The 12-week training program based on systematic internal and external load monitoring produced substantial and statistically significant physiological adaptations across all measured parameters. Compliance with the program was high, with participants completing an average of 93.7% of scheduled training sessions over the intervention period. No serious adverse events or training-related injuries requiring cessation of participation were recorded, a finding consistent with the carefully managed progressive loading strategy employed throughout the program.

Aerobic capacity, as estimated by the 20-meter multistage fitness test, improved markedly across the group. Pre-intervention VO₂max values averaged 42.3 ± 3.1 mL/kg/min, which is broadly consistent with normative data for moderately trained adolescent athletes in tropical climates. Following the 12-week program, post-intervention VO₂max reached a mean of 48.7 ± 2.9 mL/kg/min, representing an absolute improvement of 6.4 mL/kg/min and a percentage gain of approximately

15.1%. This change was highly statistically significant ($t(29) = 14.82$, $p < 0.001$) with a large effect size (Cohen's $d = 2.17$), indicating that the structured monitoring-guided program was highly effective in stimulating aerobic development. The magnitude of improvement observed exceeds that reported in many unmonitored youth training programs documented in the literature, where VO_{2max} gains of 5 to 8 percent over comparable durations are more typical, suggesting that the individualized load management approach contributed meaningfully to the superior outcomes in this cohort (Baquet et al., 2020).

Resting heart rate, a well-established indicator of cardiovascular efficiency and parasympathetic nervous system activity, demonstrated a clinically meaningful and statistically significant reduction over the intervention period. Pre-intervention mean resting heart rate was 74.2 ± 5.3 beats per minute (bpm), which fell within the expected range for adolescents with moderate prior training backgrounds. Following the 12-week program, mean resting heart rate declined to 62.8 ± 4.7 bpm, a reduction of 11.4 bpm representing a 15.4% improvement. The paired t-test confirmed the significance of this change ($t(29) = 13.47$, $p < 0.001$), and the effect size was large (Cohen's $d = 2.31$). This degree of resting bradycardia is consistent with cardiac adaptations including increased stroke volume and enhanced vagal tone that are well-characterized in trained individuals (Faigenbaum et al., 2020). The heart rate monitoring data collected during training sessions throughout the program provided additional insight, showing a systematic trend toward lower submaximal exercise heart rates at equivalent absolute workloads as the program progressed, indicating improving cardiovascular efficiency independent of perceived exertion changes (Buchheit & Laursen, 2020).

Blood lactate threshold, assessed through graded exercise testing with fingertip sampling, showed a substantial improvement following the intervention. Pre-intervention lactate threshold occurred at a mean exercise intensity corresponding to 72.4% of estimated VO_{2max} , while post-intervention threshold was identified at 85.8% of estimated VO_{2max} , representing an absolute shift of 13.4 percentage points and a relative improvement of 18.5%. This finding is particularly significant from an athletic performance perspective, as a higher lactate threshold relative to VO_{2max} allows athletes to sustain higher exercise intensities aerobically for longer durations without progressive acidosis-related fatigue. The improvement observed reflects enhanced mitochondrial density, increased activity of key oxidative enzymes, and improved capacity for lactate clearance, all characteristic adaptations of aerobic training. The systematic progression of aerobic base training volume in the early mesocycles, guided by TRIMP monitoring to ensure appropriate cardiovascular stimulus, is likely the primary driver of this metabolic adaptation (Ramadhan & Santoso, 2022).

Muscular performance, assessed through the standardized squat jump and countermovement jump protocol, also improved significantly over the 12-week period. Squat jump height increased from a pre-intervention mean of 28.4 ± 4.2 cm to a post-intervention value of 34.7 ± 3.8 cm, representing a 22.2% improvement ($t(29) = 11.93$, $p < 0.001$, $d = 1.57$). Countermovement jump height showed a similar pattern, increasing from 31.2 ± 4.6 cm to 38.6 ± 4.1 cm, a 23.7% improvement ($t(29) = 12.44$, $p < 0.001$, $d = 1.69$). Peak force values derived from the force plate increased by 19.8% and rate of force development improved by 26.3%, indicating enhanced neuromuscular recruitment efficiency alongside structural muscular adaptations. These gains in explosive lower body power are particularly relevant for the predominantly team sport athletes in the cohort, for whom acceleration, jumping, and change of direction capabilities are key performance determinants. The strength and power mesocycle emphasis introduced in weeks five through eight, alongside ongoing aerobic and technical training, appears to have created optimal conditions for simultaneous development of multiple physical capacities (Prasetyo & Nugroho, 2021).

Internal load data collected throughout the intervention revealed a coherent progressive loading pattern consistent with the planned program structure. Mean sRPE-based training load during the first week was 287 ± 43 AU, rising progressively to a peak of 623 ± 58 AU in week ten before tapering to 398 ± 47 AU in week twelve. TRIMP values followed a similar trajectory, confirming that athlete perceptions of effort were broadly congruent with physiological strain as measured by heart rate. The correlation between weekly sRPE-derived training load and TRIMP was strong across the full program ($r = 0.89$, $p < 0.001$), replicating findings from previous validation studies and supporting the

utility of session RPE as a cost-effective primary monitoring tool in resource-limited settings (Haddad et al., 2021).

The acute-to-chronic workload ratio remained within the optimal zone of 0.8 to 1.3 for 87.4% of all athlete-week observations throughout the program, reflecting successful implementation of the progressive loading protocol. In the minority of cases where the ACWR briefly exceeded 1.3, these were concentrated in the transition between mesocycles two and three when training intensity was deliberately elevated. Importantly, no injuries occurred during these high-load periods, suggesting that the preceding chronic load buildup provided sufficient preparedness for the acute demands. Monotony indices remained low throughout the program, averaging 1.48 ± 0.31 , indicating that training was adequately varied to prevent excessive repetitive strain (Gabbett, 2020).

External load data from GPS tracking revealed progressive increases in training volumes across high-speed running and sprint work categories consistent with the mesocycle structure. Total weekly distance increased from an average of 14.2 ± 2.3 km in week one to 22.8 ± 2.9 km at peak loading in week ten. High-speed running distance increased by 68.3% from baseline to peak loading phase, and sprint distance more than doubled between the general preparation and specific preparation phases as speed-oriented training sessions were progressively introduced. PlayerLoad data showed a corresponding increase, indicating greater total mechanical stress on the musculoskeletal system, which is consistent with the neuromuscular adaptation data obtained from jump testing. The correspondence between external load progression and the magnitude of physiological adaptations observed provides further support for the load monitoring framework as both a prescriptive and evaluative tool (Bourdon et al., 2021).

Gender-stratified analysis revealed that while both male and female athletes demonstrated significant improvements across all parameters, the magnitude of certain adaptations differed between groups. Male athletes showed larger absolute gains in VO_{2max} (7.1 vs. 5.4 mL/kg/min) and jump height (25.3% vs. 18.6%), which is consistent with testosterone-mediated anabolic advantages during late adolescence. Female athletes, however, showed proportionally similar improvements in resting heart rate reduction and lactate threshold shift, suggesting that the aerobic and metabolic adaptations are relatively independent of sex hormone effects at these training intensities (Soligard et al., 2020). These findings align with previous Indonesian research demonstrating that properly structured training programs can produce robust physiological benefits in female adolescent athletes when load is appropriately managed and individualized.

From a practical standpoint, the findings of this study support the integration of systematic load monitoring into youth sports training programs at Indonesian universities and sports academies. The combination of relatively low-cost tools, specifically the sRPE method and basic heart rate monitoring, with periodic fitness testing provided coaches with actionable information that guided effective load prescription. The weekly load reports generated from sRPE and TRIMP data enabled timely adjustments to training when individual athletes showed signs of excessive fatigue, as evidenced by sustained high perceived exertion relative to objective workload metrics. This individualization capability is particularly valuable in group-based training settings where uniform prescriptions may be inappropriate for the full distribution of athlete capacities and recovery rates (Matos et al., 2021; Impellizzeri et al., 2020).

The physiological adaptations documented in this study are consistent with established principles of training science but extend the evidence base by demonstrating their applicability in the specific context of adolescent athletes in Eastern Indonesia. The hot and humid climate of Makassar, characterized by year-round temperatures exceeding 28 degrees Celsius and high relative humidity, imposes additional thermoregulatory demands on athletes that elevate internal load for any given external workload. Heart rate monitoring was particularly valuable in this context, as cardiovascular drift associated with heat stress can elevate heart rate responses independently of exercise intensity, potentially confounding RPE-based load estimates. The dual monitoring approach was therefore not merely methodologically comprehensive but climatically necessary to accurately capture true physiological strain in this population (Ramadhan & Santoso, 2022).

CONCLUSION

The findings of this study provide compelling evidence that a 12-week training program guided by systematic monitoring of both internal and external training loads produces significant and practically meaningful physiological adaptations in adolescent athletes. Substantial improvements were observed in aerobic capacity (VO₂max), resting heart rate, blood lactate threshold, and muscular explosive performance, all with large effect sizes confirming the practical significance of these changes beyond statistical significance alone. The coherence between internal load indicators (sRPE and TRIMP) and external load metrics (GPS-derived distance and speed data) validated the multi-modal monitoring framework employed and demonstrated its feasibility in a university sports science setting in Indonesia.

The maintenance of acute-to-chronic workload ratios within recommended ranges throughout the program, combined with zero injury incidence, suggests that load monitoring not only optimizes adaptation but also supports athlete health and availability. These outcomes underscore the importance of evidence-based load management in youth athletic development programs, where the dual imperatives of maximizing trainability windows and protecting developing musculoskeletal systems demand precise and individualized training prescription. The study also demonstrates that the combination of accessible, low-cost tools such as session RPE with heart rate monitoring can provide sufficient monitoring fidelity to guide effective training programs in resource-constrained settings typical of many Indonesian educational institutions.

Future research should extend these findings by incorporating longer intervention periods, including control groups to isolate training effects from maturation, examining the influence of nutrition and sleep on load-adaptation relationships, and exploring the longitudinal tracking of athletes across multiple training seasons. Additionally, investigating the psychological dimensions of load monitoring, including athlete engagement with feedback data and coach-athlete communication around load management decisions, would contribute to a more holistic understanding of how monitoring systems can be optimized for youth sports contexts in Indonesia and similar developing sporting environments.

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